

The effect of Triaxiality on the dynamics of Triple Supermassive Black Holes in a cosmological context

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Introduction

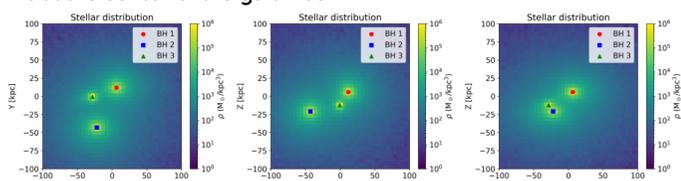
Supermassive Black Holes (hereafter SMBHs), with mass ranges within $10^5 - 10^{10} M_{\odot}$ are present in the centers of the vast majority of galaxies. In the post merger phase of the galaxy mergers, these SMBHs sink to the center of the galaxy through dynamical friction with other stellar bodies and particles and coalesce together to form a binary or triple system.

The timescale from the merger of the galaxies to the coalescence of the black holes can vary significantly depending on the remnant's matter distribution and the binary parameters, with timescales reaching from 50 Myr up to 1 Gyr. It is possible that a third galaxy joins a galaxy, which still contains an SMBH binary and creates a triple SMBH system, or that even three (or more) galaxies directly merge simultaneously.

- Study the effect of Triaxial galaxies on the dynamics of triple SMBHs using high-resolution N-body re-simulation with initial conditions from cosmological simulations
- Track the orbital evolution from the galactic inspiral to the formation of hard binaries at sub-parsec separation along with the formation of a Hierarchical or a Chaotic Triple and use the observed hardening rates to project the time of coalescence.
- Track the triaxial shape evolution of the galaxy remnant and check it's effect on the outcome of the triple system.

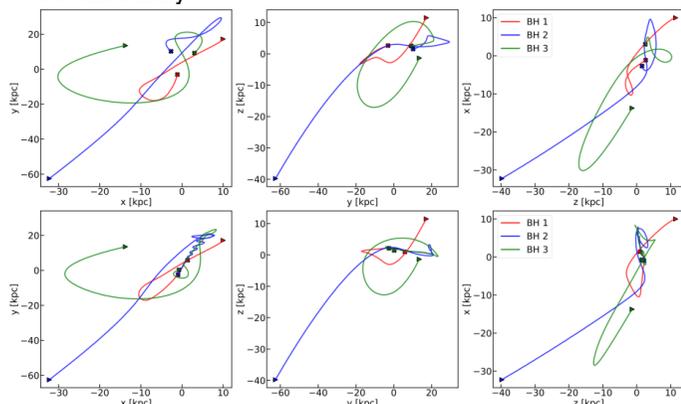
Methods and Initial conditions

- Create 3-galaxy triaxial initial conditions with Dark matter, Gas and Stars using **AGAMA** galaxy modelling software (Vasiliev et al., 2019).
- Initial conditions of the SMBHs from the **ROMULUS-25** cosmological simulation (Tremmel et al. 2017), and the triaxial shape of the galaxy from Butsky et al. (2016).
- **BONASAI2**: Tree code with ~ 10 million particles for each galaxy for the early evolution of the global galaxy merger phase and the decay of the SMBHs to the center of the merger remnant due to dynamical friction [color coded as Grey] (Bédorf et al. 2012).
- **ϕ -GPU**: Direct N-body code with individual block time steps for the hardening phase of SMBHs and correctly resolve the 3-body interactions close to SMBHs [color coded as white] (Berczik et al., 2011).
- **Post-Newtonian (PN) approximation**: When the Black holes reaches separation of 1000Rs and move towards the relativistic regime and probable GW emission.
- Three SMBHs of masses $\sim 10^7 M_{\odot} - 10^8 M_{\odot}$, initial separation of 10-100 kpc.
- **Dehnen** density profile with the Dark matter, Gas and Stars components along with the three SMBHs at the center of the galaxies.



Orbital evolution of the Triple SMBH

- The orbital evolutions forms a binary which have orbits around the most massive BHs.
- From time to time there are chaotic three-body encounters of the SMBHs which switches the members of the binary.



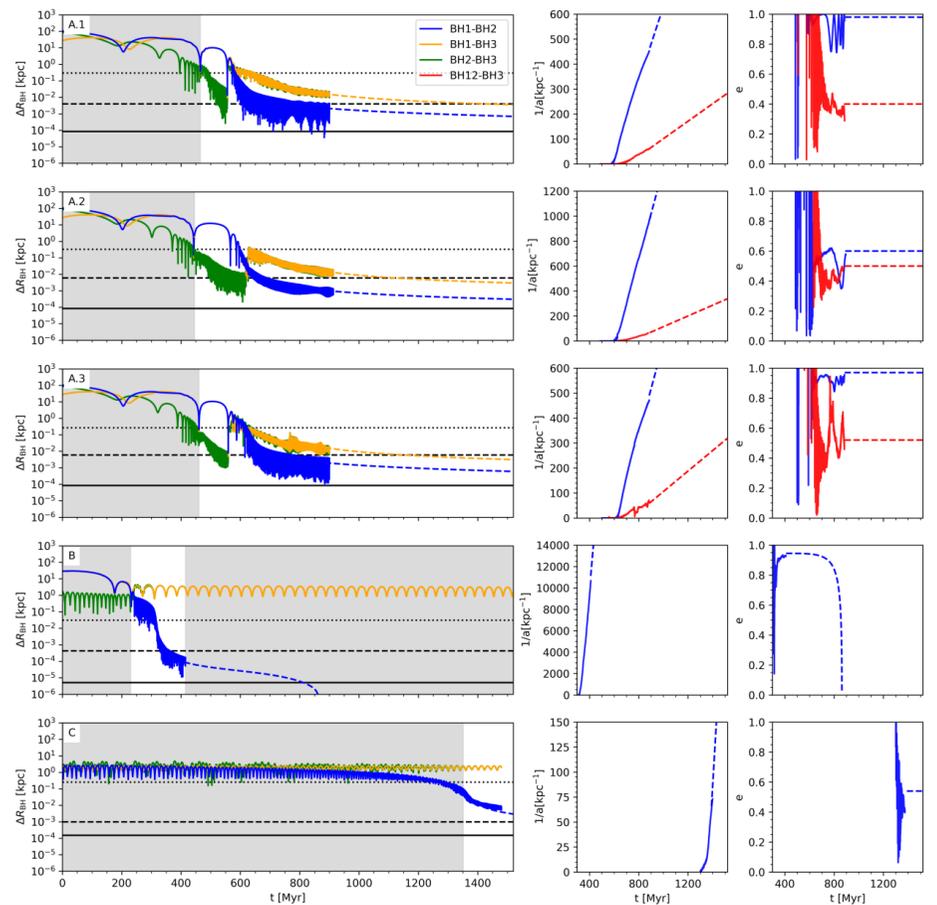
Acknowledgement

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Quantitative analysis of the Triple SMBH

- 5 models having different stellar density profiles and triaxiality for each galaxies with a total of $\approx 26 \times 10^6$ particles for model A and B, and $\approx 19 \times 10^6$ particles for model C.
- Reduce the total particles close to the inner 10kpc of the SMBHs when switching to ϕ -GPU.
- Evolution of Black Hole separation, semi-major axis and eccentricity where the dotted, dashed, and solid lines respectively mark the influence radius, hardening radius, and the factor 1000 of the Schwarzschild radius of BH1.



Evolution of the Triaxial shape

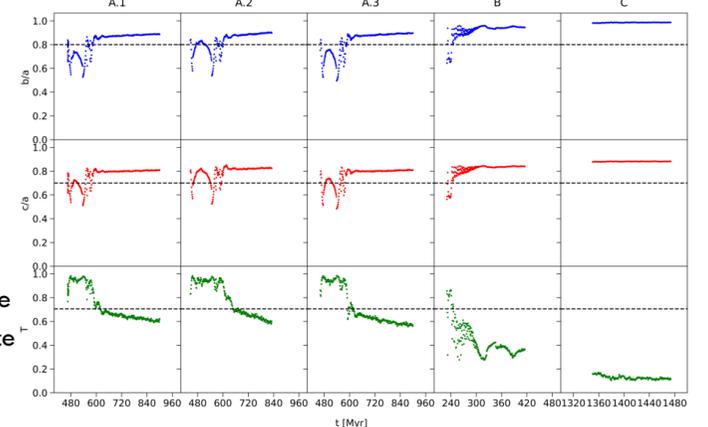
- Time evolution of galaxy axis ratios and triaxiality parameter at a distance of 1 kpc from the center.

$$T = \frac{a^2 - b^2}{a^2 - c^2}$$

where, $0 \leq T \leq 1$

$T = 0$: perfectly oblate

$T = 1$: perfectly prolate



Merging Time

- We take the orbital averaged hardening rate by GW emission from the empirical **Peter and Mathews** (1963) formula assuming a constant eccentricity.
- We add the stellar hardening estimated from the simulation and calculate the estimated merging time of the hard binary.

$$\frac{d}{dt} \left(\frac{1}{a} \right) = H \frac{G\rho}{\sigma}$$

$$\frac{d}{dt} \left(\frac{1}{a} \right) = s_{SH} + \frac{64 G^3 \mu M^2}{5 c^5 a^5} \frac{1 + 73/24 e^2 + 37/96 e^4}{(1 - e^2)^{7/2}}$$

Property	A.1	A.2	A.3	B	C
s_{12}	1.50	3.64	1.82	131.40	2.10
H_{12}	52.30	41.52	11.3	5.75	6.68
$t_{c,12}$ (in Myr)	2863	7400	3160	863	13409

Conclusion

- In all the models the two heaviest black holes form a bound binary, whereas the fate of the third lightest black hole varies. It either forms a stable hierarchical triple (A.1, A.2, and A.3) or never becomes bound and remains on a wide galactic orbit around the inner binary (B and C).
- Although the triaxial structure evolves during the initial interaction phase, once the binary settles, the remnant in all simulations retains a shape that does not exhibit any significant departure from the original triaxial structure of the progenitor galaxies, as compared to spherical galaxies.
- The merging time of the models is different because of different hardening rate of the binary system, which actually depends on the details of the orbit.



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